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Summary of NASA/DOE Aileron-Control Development Program for Wind Turbines

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Work performed for
U.S. DEPARTMENT OF ENERGY
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SUMMARY OF NASA/DOE AILERON-CONTROL DEVELOPMENT

PROGRAM FOR WIND TURBINES

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SUMMARY

This paper will briefly trace the development of aileron-control for wind turbines. Then selected wind tunnel test results and full-scale rotor test results will be presented for various types of ailerons. Finally, the current status of aileron-control development will be discussed.

Aileron-control was considered as a method of rotor control for use on wind turbines based on its potential to reduce rotor weight and cost. Following an initial feasibility study, a 20 percent chord aileron-control rotor was fabricated and tested on the NASA/DOE Mod-0 experimental wind turbine. Results from these tests indicated that the 20 percent chord ailerons regulated power and provided overspeed protection, but only over a very limited windspeed range.

The next aileron-control rotor to be tested on the Mod-0 had 38 percent chord ailerons and test results showed these ailerons provided overspeed protection and power regulation over the Mod-0's entire operational windspeed range.

INTRODUCTION

As part of the DOE Wind Energy Program, NASA Lewis Research Center has been involved in the development of aileron controls for use on horizontal-axis wind turbines. This work had its beginning in 1979, when aileron-control was seriously considered as an alternate to blade pitch control on horizontal-axis wind turbines.

This method of rotor control consists of placing a control surface on the trailing-edge of the rotor blade, in the same way control surfaces are placed on the trailing-edge of aircraft wings. As with the aircraft wing, the ailerons change the lift and drag characteristics of the basic airfoil as a function of the deflection angle, producing corresponding changes in rotor torque. It is these changes in rotor torque which enable the ailerons to regulate rotor speed or rotor power output.

On a wind turbine rotor blade, the ailerons are deflected toward the low pressure surface of the airfoil to produce a braking effect. However, the ailerons on an aircraft wing are deflected toward the high pressure surface to increase lift, during a takeoff or landing condition.

Figure 1 shows cross-sectional views of two typical aileron configurations evaluated for wind turbine rotor control. The primary difference between these two configurations is the length of the lower control surface. Note that the balanced aileron has an extended lower control surface, relative to the plain aileron.

With the emphasis on developing cost-effective wind turbines, it was felt that aileron-control could make a contribution to this effort by reducing rotor weight and cost.

• Aileron-control has the potential to reduce rotor weight because:

(1) The actuator is smaller and lighter than are the actuators for full or partial-span control rotors.

(2) The rotor blade structure near the tip interface does not need additional strengthening to support a partial-span control actuator. Thus, the blade structure for an aileron-control rotor weighs less than that for a partial-span control rotor.

• Aileron-control has the potential to reduce rotor cost because it can be utilized on a fixed pitch rotor, which should be less expensive than a partial-span control rotor.

A wealth of information has been obtained from full-scale rotor tests and wind tunnel tests of various aileron-control configurations. Therefore, the objectives of this paper are to highlight some of the more significant wind tunnel and full-scale rotor test results, and to summarize the current status of aileron-control as a means for rotor overspeed protection and power regulation on horizontal-axis wind turbines.

This paper will first present selected wind tunnel test results to illustrate several parameters affecting aileron-control effectiveness. Next, full-scale rotor test results for the 20 and 38 percent chord aileron-control rotors will be discussed. Finally, the current status of aileron-control will be summarized, followed by recommendations for future aileron-control development work.

CHRONOLOGY OF AILERON DEVELOPMENT

Considering this potential for reduction in rotor weight and cost, it was decided to investigate the feasibility of using aileron-control on horizontal-axis wind turbines. Wichita State University conducted the feasibility study in 1980, and concluded that ailerons would provide rotor speed control following a loss-of-load, and also regulate rotor power (ref. 1).

Based on these results, two 20 percent chord aileron-control tip sections were designed and fabricated for test on the Mod-0 Experimental Wind Turbine. Wind tunnel tests of a 20 percent chord aileron section (ref. 2) were also conducted in parallel with the fabrication of the 20 percent chord aileron-control tip sections. Unfortunately, these wind tunnel test results suggested that the 20 percent chord ailerons had less aerodynamic braking effectiveness than originally predicted in the Feasibility Study (ref. 1). This result was later verified by full-scale rotor tests of the 20 percent chord aileron-control tip sections in 1983.

These tests indicated that the 20 percent chord ailerons were effective over a limited windspeed range. Thus, ailerons with more control effectiveness were required (i.e. - ailerons which would provide better loss-of-load overspeed protection, as well as regulate power over the Mod-0's entire operational windspeed range).

Following these full-scale rotor tests of the 20 percent chord ailerons, Wichita State University conducted additional wind tunnel tests on various aileron and spoiler configurations up to 38 percent chord length. These wind tunnel tests were intended to identify aileron configurations with improved aerodynamic braking characteristics (ref. 3). Results from these investigations indicated that aerodynamic braking effectiveness could be improved by increasing the aileron chord length and also the maximum aileron deflection angle. These results were incorporated into the design of the 38 percent chord aileron, which was the next aileron configuration tested on the Mod-0.

During the fall of 1983, three 38 percent chord aileron-control tip sections were fabricated. Two of these were installed on the Mod-0 for full-scale rotor tests, while the third tip section was tested in the NASA Langley 30' x 60' wind tunnel. These aileron-control tip sections were originally intended to validate aileron-control for use on General Electric's 7.3 megawatt Mod-5A wind turbine design (ref. 4). However, following termination of the Mod-5A program, these aileron-control tip sections were used primarily to gather aerodynamic braking and power regulation information for the NASA aileron development program.

Full-scale rotor tests of the 38 percent chord aileron-control tip sections were conducted on the Mod-0 wind turbine from December 1983 through June 1984. Results from loss-of-load shutdown tests conducted with this aileron configuration indicated that the 38 percent chord ailerons were much better aerodynamic braking devices than the 20 percent chord ailerons (refs. 5 and 6). Also, the 38 percent chord ailerons effectively regulated power output over the entire operational windspeed range of the Mod-0 (ref. 7).

Wind tunnel tests of the third 38 percent chord aileron-control tip section were conducted in parallel with the full-scale rotor tests described above (ref. 8). Lift and drag data (C_l and C_d) were obtained to help predict the aerodynamic braking characteristics of the 38 percent chord aileron-control tip sections tested on the Mod-0. Figure 2 shows the full-scale aileron-control tip section mounted in the 30' x 60' wind tunnel, while figure 3 presents some typical lift and drag data obtained from these tests.

The foregoing is a brief chronological record of the NASA/DOE aileron development activities from 1979 through 1984. Therefore, the results discussed in this paper represent the aileron-control development status as of 1984.

WIND TUNNEL TEST RESULTS

Wind tunnel tests of different aileron configurations were an integral part of the NASA aileron development program. The wind tunnel proved to be a valuable tool, not only because potential aileron configurations could be compared directly under controlled conditions; but also, because lift and drag data from these wind tunnel tests were utilized to predict aileron-control rotor loads and performance. The majority of these tests were performed under research grants to the Aeronautical Engineering Department at Wichita State University. A few additional tests were conducted at Ohio State University and NASA Langley Research Center. A list of these aileron-control wind tunnel tests is found in table I.

Though wind tunnel test results of an airfoil section are generally expressed in terms of lift coefficient (C_l) and drag coefficient (C_d), this paper will describe aileron wind tunnel results in terms of the Chordwise Force Coefficient (C_c, also called Suction Coefficient). C_c is a combination of both the lift and drag forces as shown in the equation below:

$$C_c = C_l \sin(\alpha) - C_d \cos(\alpha) \tag{1}$$

where α is angle of attack.

The reason for using C_c to describe aileron-control braking effectiveness is that only the chordwise force produces torque (assuming a wind turbine blade with no pitch or twist). Because of this direct relationship between chordwise force and rotor torque, C_c serves as a convenient parameter for evaluating an aileron's aerodynamic braking effectiveness. If C_c is negative, this will correspond to a negative torque, which in turn produces a rotor deceleration. Therefore, it is desirable to have a negative value of C_c from 0 to 90 degrees angle of attack.

When considering rotor speed and power control, it is desirable to have systematic changes in C_c as a function of aileron deflection. Ideally, C_c should decrease monotonically with increased negative aileron deflection. This characteristic should be exhibited over the angle of attack range the ailerons would experience in normal wind turbine operation (approximately 0° to 20°).

As mentioned earlier, selected wind tunnel results will be used to highlight several parameters affecting the aerodynamic braking effectiveness of ailerons. One of these parameters is the aileron chord length.

The effect of aileron chord length on C_c is illustrated in figure 4 for 20 and 30 percent chord ailerons deflected -60° (refs. 2 and 3). For $\alpha < 25°$, the C_c curve for the 30 percent chord aileron lies considerably below the 20 percent chord aileron lies considerably below the 20 percent chord aileron curve. Thus, increasing the aileron chord length from 20 to 30 percent of blade chord markedly improved the aerodynamic braking characteristics, by causing C_c to remain negative over a wider angle of attack range. The positive C_c spike has also been greatly reduced for the larger chord aileron.

To show the combined effect of a larger chord length coupled with a greater negative aileron deflection range, an additional C_c curve has been included in figure 4. This is the -90° deflection curve for the 30 percent chord aileron, which is represented by the dotted line. Note that this curve exhibits the best aerodynamic braking characteristics shown so far. Though not shown in this figure, C_c remains negative until 80° angle of attack. Generally speaking, increasing both the aileron chord length, and the aileron deflection angle will contribute to a better aerodynamic braking device.

It should be mentioned that there is a practical limit to increasing the aileron chord length; for example, a 100 percent chord aileron would be a partial-span pitch-control device. Also, for each particular aileron configuration, there is an optimum deflection angle which produces the best overall aerodynamic braking characteristics. Of the various aileron configurations tested, the -90° deflection angle appeared to have the best overall C_c characteristics (ref. 3).

Another significant parameter affecting aileron braking effectiveness is Reynolds Number (ref. 3). Figure 5 shows the effect of Reynolds Number (Re) on C_c for a 30 percent chord balanced aileron deflected -90°. The solid curve represents the C_c values obtained from Re = 600,000 data, while the dashed curve represents C_c from Re = 900,000 data. The two curves are basically the same, except for the large positive valued C_c "spike" evident on the Re = 900,000 curve. The conclusion drawn from comparing these two curves, is that increased Reynolds Number tends to reduce the braking effectiveness of an aileron.

There is a modification to the aileron airfoil section which appears to counteract the effect of increased Reynolds number on C_c. This modification consists of inserting a vent just ahead of the deflected aileron (ref. 3). As the aileron is deflected, the vent is uncovered, and air is allowed to flow between upper and lower airfoil surfaces.

The effect of venting on C_c is illustrated by the dotted curve in figure 5. Note that the positive valued C_c spike is greatly reduced for the vented aileron. In fact the peak C_c value is at most, just slightly positive. However, for $\alpha > 30°$ it appears that venting tends to raise the C_c curve relative to the unvented case. As discussed in reference 3, the values of C_c for $20° < \alpha < 35°$ are more critical for aileron braking effectiveness, than are the values of C_c for $\alpha > 35°$. Thus, the slight positive increase in C_c at higher angles of attack is not as significant, as the suppression of the C_c spike for $20° < \alpha < 35°$.

FULL-SCALE ROTOR TEST RESULTS

Not only were wind tunnel tests conducted on aileron-control airfoil sections, but several aileron configurations were also tested on the Mod-0 Experimental Wind Turbine. Full-scale rotor test results from two basic aileron-control configurations will be summarized in this paper - 20 percent chord plain aileron, and 38 percent chord ailerons, both plain and balanced. Table II contains a list of these full-scale aileron-control rotor tests.

A planform of the basic aileron-control rotor is shown in figure 6. The inboard portion of the rotor was identical for both the 20 and 38 percent chord aileron-control rotors, with differences between the two configurations occurring in the respective aileron-control tip sections. Figure 7 is a planform of the basic tip section illustrating differences in geometry and aileron characteristics between the 20 and 38 percent chord aileron-control tip sections.

The primary objectives for conducting the full-scale aileron-control rotor tests were:

(1) To determine how effectively each aileron configuration would control overspeed, and decelerate the rotor to a low equilibrium rpm, preferably zero, following a loss of generator load. (Aerodynamic Braking Effectiveness)

(2) To determine how effectively each aileron configuration would regulate power output, over the Mod-0 operational windspeed range of 4 to 18 mps. (Power Regulation)

Aerodynamic Braking Effectiveness

Loss-of-load shutdown tests and no-load equilibrium rpm tests were conducted to evaluate the aerodynamic braking effectiveness of the 20 and 38 percent chord aileron-control rotors following a loss of generator load. Figure 8 is a plot of an actual loss-of-load shutdown time history for the 38 percent chord aileron-control rotor. It illustrates how the rotor first overspeeds and then gradually approaches a stable (equilibrium) rpm.

Also shown in figure 8 is a predicted curve, which was calculated using the Mod-0 Emergency Shutdown Model (ref. 9). This computer program treated the rotor and drivetrain inertia as a large "flywheel" with aerodynamic and drivetrain frictional torques acting on it. As a general rule, the Emergency Shutdown Model predictions agreed very well with experimental loss-of-load shutdown test results, and no-load equilibrium rpm test results. This was true for both the 20 and 38 percent chord aileron-control rotors.

<u>Loss-of-Load Shutdown Tests</u>. - For these tests, the generator load was dropped and after a 1 sec delay, the ailerons began deploying at a constant rate. These tests were intended to evaluate the effect of windspeed on peak rotor speed, at various deflection rates. Only preliminary shutdown tests were conducted on the 20 percent chord aileron-control rotor due to its limited aerodynamic braking effectiveness. Hence, shutdown test results will only be presented for the 38 percent chord aileron-control rotor.

Figure 9 is a plot of peak rotor speed following loss-of-load for the 38 percent chord plain aileron. Experimental and predicted peak rotor speeds are shown for aileron deflection rates of 15, 20, and 25 deg/sec. In general, there is very good agreement between the experimental and predicted results. Also, figure 9 illustrates that the peak rotor speed will increase with increasing windspeed.

There appears to be a slight correlation between the experimental peak rotor speeds and deflection rate, but more experimental data at higher windspeeds would be required to firmly establish this relationship. Based on the predicted peak rotor speeds, shown in figure 9, an increase in deflection rate should produce a decrease in observed peak rotor speed (ref. 5).

Though not shown, peak rotor speed characteristics for the 38 percent chord balanced aileron were similar to those trends seen in figure 9 for the plain aileron. In fact, experimental and predicted peak rotor speeds for the plain aileron configuration were almost identical to those characteristics for the balanced aileron configuration.

<u>No-Load Equilibrium Rotor Speed Tests</u>. - The purpose of these tests was to determine the relationship between no-load equilibrium rpm and windspeed.

The procedure for these tests was different than that employed for the loss-of-load shutdown tests. Initially, with the Mod-0 at rest, the ailerons were set at a fixed deflection angle. Then the Mod-0 was "motored" to 8 rpm; at which point, the motoring was stopped and the aileron-control rotor was allowed to freewheel as a function of windspeed.

Figure 10 is a summary of the no-load equilibrium rpm characteristics for the 20 and 38 percent chord ailerons. No-load equilibrium rpm is plotted versus windspeed for various aileron deflection angle settings. Also, the corresponding equilibrium tipspeed ratio (λ_{EQ}) is shown for each curve.

The improvement in aerodynamic braking effectiveness due to a larger chord aileron can be seen by comparing the -60° deflection curves for the 20 and 38 percent chord ailerons. A further comparison of the -90° and -60° deflection curves for the 38 percent chord ailerons, illustrates the additional improvement in braking effectiveness due to increased aileron deflection angle. Thus, increasing the chord length from 20 to 38 percent and also increasing the maximum aileron deflection angle from -60° to -90°, produced a very significant reduction in equilibrium tipspeed ratio from 5.4 (20 percent chord aileron) to 1.9 (38 percent chord plain aileron) or 2.1 (38 percent chord balanced aileron). These equilibrium rpm test results substantiate the wind tunnel test results presented in figure 3 and indicate that the 38 percent chord plain aileron had the best aerodynamic braking characteristics of all the aileron configurations tested on the Mod-0.

Mean flatwise and chordwise bending moments were measured at the root of the rotor blade during the loss-of-load shutdown tests (ref. 10). During a typical loss-of-load shutdown, both the mean flatwise and chordwise moments will change (or reverse) sign as the ailerons are deflected towards a fully deployed condition. A comparison of the maximum (reversed) mean flatwise moments for a tip-control rotor and the 38 percent chord aileron-control rotor revealed that these "rotor loads" were similar in magnitude. Also, the change in mean chordwise moment was relatively small compared to the cyclic chordwise moment due to gravity. Thus, the aileron-control rotor shutdown loads were comparable to tip-control rotor shutdown loads.

Speed Regulation (Off-Line)

These tests were intended to evaluate the ailerons ability to maintain a constant rotor speed. For these tests, the Mod-0 was operated in the speed-control mode, such that the aileron deflection angle was varied to maintain the rotor speed setpoint.

The 38 percent chord plain aileron-control rotor was tested at rotor speeds of 10, 15, and 20 rpm for windspeed of 4 to 8 mps. Test results indicated that the ailerons maintained the rotor speed setpoint within several tenths of an rpm. Thus, the 38 percent chord ailerons accurately regulated rotor speed near the Mod-0's "cut-in" windspeed of 4 mps.

The Mod-0 generator was routinely connected to the utility grid without difficulty. This was due to the overrunning clutch on the Mod-0's high speed shaft, and to the effective speed regulation capability of the 38 percent chord ailerons.

Power Regulation

Power regulation tests were conducted on the 20 and 38 percent chord aileron-control rotors. The purpose of these tests was to evaluate the ability to maintain a prescribed power output. Therefore, the Mod-0 was operated in a power-control mode, such that the aileron deflection angle was varied to maintain the power setpoint.

Figure 11 is a comparison of 0 kW power regulation test results for the 20 and 38 percent chord aileron-control rotors. Though the 0 kW setpoint does not represent a practical wind turbine operating condition, it does provide a significant test of an aileron-control rotor's power regulation capability. Mean power output is plotted versus mean windspeed for both aileron-control rotors.

A "bins" analysis was performed on the power values shown in figure 11. The circles and squares represent median power values in each windspeed bin, for the 20 and 38 percent chord aileron-control rotors, respectively. The horizontal bars above and below each median value represent an interval of one standard deviation (1σ) about the median.

Figure 11 illustrates that the 20 percent chord ailerons effectively regulated power for windspeeds up to 7 mps, while the 38 percent chord ailerons regulated power up to 16 mps. Though not shown here, other power regulation data suggest that the 38 percent chord ailerons are effective over a windspeed range extending up to 20 mps (ref. 7). No experimental data was obtained for windspeeds above 20 mps, so the upper windspeed limit for effective power regulation is unknown for the 38 percent chord aileron-control rotor.

The interval representing one standard deviation (1σ) about the median power value can be used as a rough measure of variability in mean power (i.e. - the smaller the interval, the better the power regulation capability). Comparing the size of these 1σ intervals for the 20 and 38 percent chord aileron-control rotors, it appears that both aileron configurations displayed a ± 3 kW variation about the median for winds below 7 mps. For winds greater than 7 mps, the 38 percent chord ailerons indicated a 1σ interval of ± 5 kW.

Generally speaking, both aileron-control rotors provided acceptable power regulation. The primary difference between the 20 and 38 percent chord aileron-control rotors was the windspeed range over which effective power regulation was maintained: the 20 percent chord aileron-control rotor regulated power over a small portion of the Mod-0's operational windspeed range, while the 38 percent chord aileron-control rotor regulated power over the entire operational windspeed range for the Mod-0 (4 to 18 mps).

Flatwise and chordwise bending moments, at the blade root, were measured during the aileron-control power regulation tests. All but the cyclic flatwise bending moments exhibited trends which were similar to those observed in tip-control rotors. The cyclic flatwise bending moment, however, tended to increase more rapidly with windspeed for the aileron-control rotors than for the tip-control rotors (ref. 10).

CONCLUDING REMARKS

Experimental wind tunnel and full-scale rotor tests have verified that aileron-control is a viable rotor control method for an intermediate size wind turbine like the Mod-0 (Re = 1 to 2 million). The 38 percent chord aileron-control rotor provided loss-of-load overspeed protection; as well as effective power regulation on the Mod-0 wind turbine.

The 38 percent chord plain aileron-control rotor had the best aerodynamic braking characteristics of all the aileron configurations tested on the Mod-0. The no-load equilibrium tipspeed ratio (λ EQ) for this aileron-control rotor with a -90° aileron deflection was 1.9. This represented a very significant improvement relative to λ EQ = 5.4 for the 20 percent chord aileron-control rotor. This improvement in aerodynamic braking was attributed to the combined effect of an increased aileron chord length and an increased maximum aileron deflection of -90°.

Further improvements in aileron-control braking effectiveness appear to be linked to the development of vented ailerons. This is especially true if aileron-control technology is to be utilized on large megawatt size wind turbines (e.g. - Mod-2) where the Reynolds Number may range from 5 to 10 million. Wind tunnel results have shown that venting is important because it counteracts the reduction in aileron-control braking effectiveness associated with increased Reynolds Number.

Therefore, it is highly recommended, that full-scale rotor tests be conducted on vented-aileron configurations, first on the Mod-0 wind turbine and then on a Mod-2 size wind turbine. These tests will provide the information necessary to validate aileron-control for use on large horizontal-axis wind turbines.

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TABLE I. - SUMMARY OF WIND TUNNEL TESTS ON AILERON-CONTROL AIRFOIL SECTIONS

Reynolds number, 10^6	Basic airfoil section, NACA	Aileron chord length, percent C	Venting	Aileron type	Aileron deflection angle, deg	Wind tunnel	Reference
0.6	23024	20	No	Plain	-60 to 60	WSU	2
.6	23024	30	No	Plain	-120 to -60	WSU	3
.6	23024	30	No	Balanced	-120 to -60	WSU	3
.6	23024	30	No	Balanced	-120 to -60	WSU	3
.6 & 1.0	23024	30	Yes	Balanced	-120 to -60	WSU	3
1.5	64621	38	No	Plain	-90 to 0	Langley 30 by 60 ft	8
1.5	64621	38	No	Balanced	-90 to 0	Langley 30 by 60 ft	8
5	64621	38	No	Plain	-90 to 0	OSU	-

TABLE II. - SUMMARY OF FULL-SCALE AILERON-CONTROL ROTOR TESTS ON ThE MOD-O WIND TURBINE

Aileron chord length, percent C	Aileron airfoil section (type)	Loss-of-load shutdown tests		No-load equilibrium rpm tests		Power regulation tests		Reference
		Deflection rate, deg/sec	Windspeed range, mps	Aileron deflection, deg	Windspeed range, mps	Power setpoint, kW	Windspeed range, mps	
20	23024 (Plain)	30	4 to 7	-60	4 to 7	0 to 50	4 to 12	5 to 7
38	64xxx (Plain)	15 to 25	4 to 12	-45 to -90	4 to 16	0 to 50	4 to 20	5 to 7
38	64xxx (Balanced)	15 to 25	4 to 12	-45 to -90	4 to 16	-------	-------	------

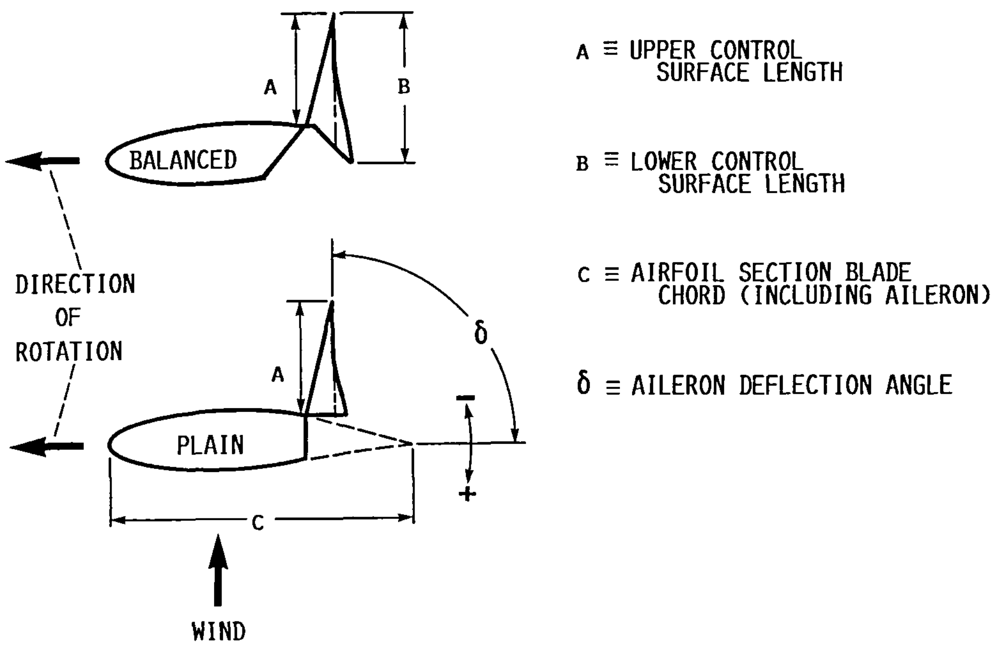


FIGURE 1.- CROSS-SECTION VIEW OF TYPICAL AILERON CONFIGURATION FOR WIND TURBINE ROTOR CONTROL.

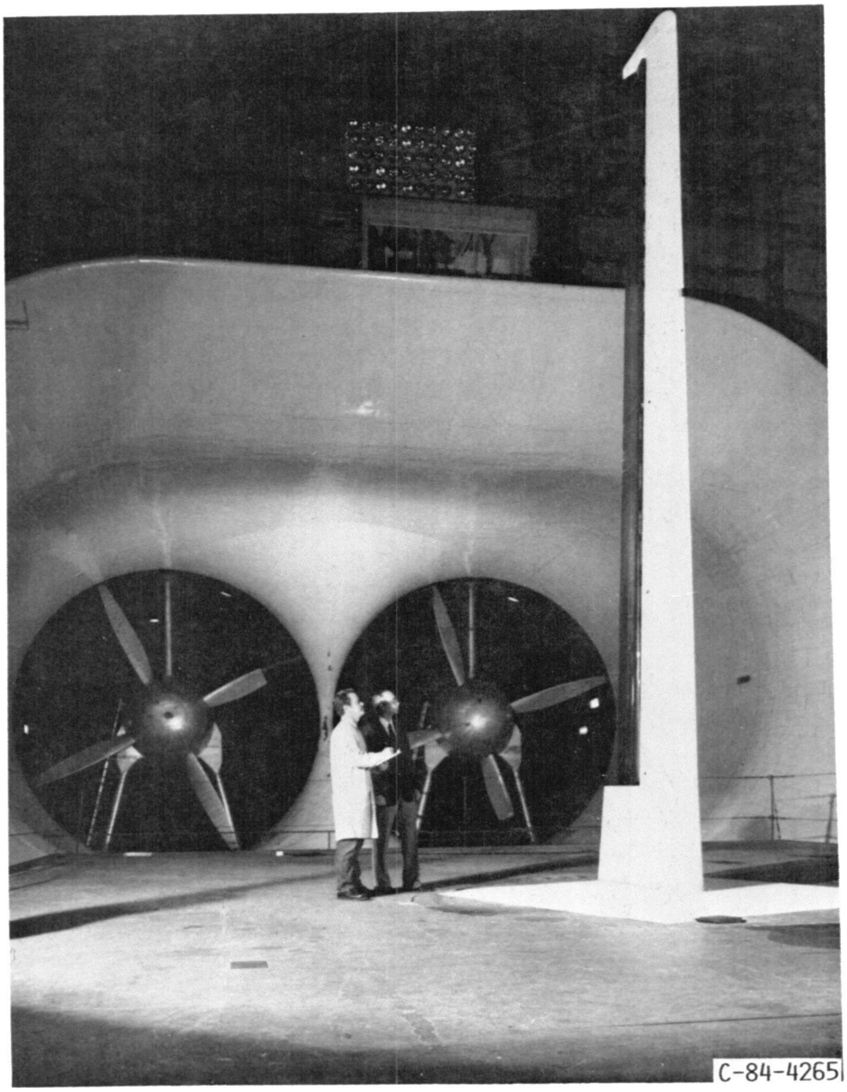
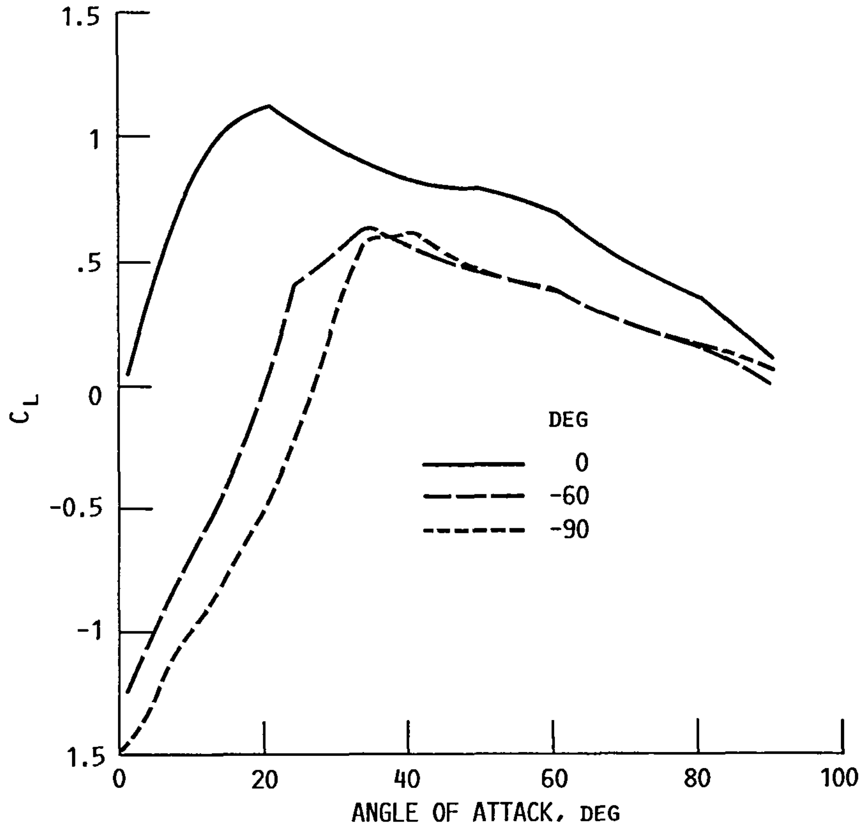
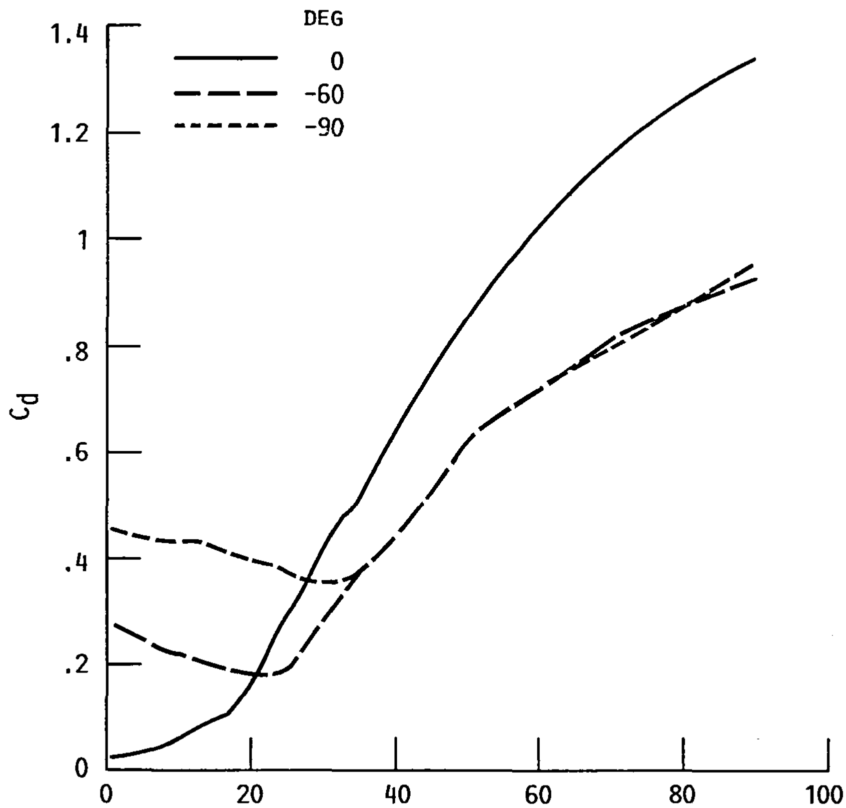


FIGURE 2. - VIEW OF 38 PERCENT CHORD AILERON - CONTROL TIP SECTION MOUNTED IN NASA LANGLEY 30′ X 60′ WIND TUNNEL.



(A) LIFT COEFFICIENT.

FIGURE 3.- LIFT AND DRAG COEFFICIENTS FOR THE 38 PERCENT CHORD AILERON-CONTROL TIP SECTION (REF. 8).



(B) DRAG COEFFICIENT.

FIGURE 3.- CONCLUDED.

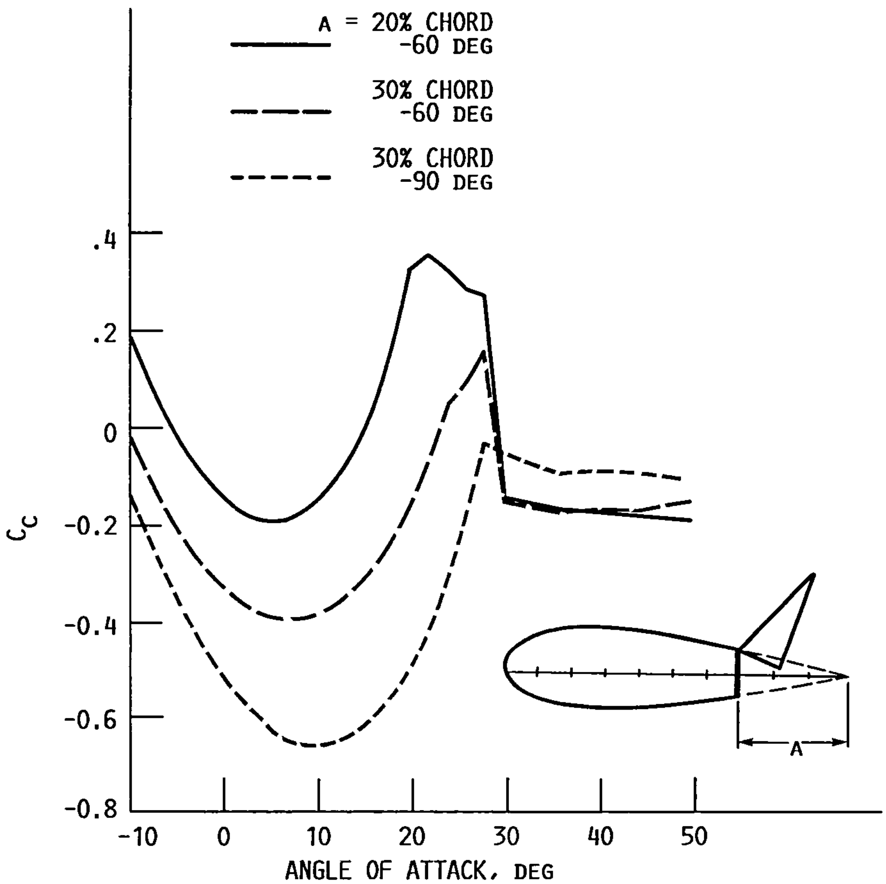


FIGURE 4.- EFFECT OF CHORD LENGTH ON CHORDWISE FORCE COEFFICIENT, C_C (REF. 3).

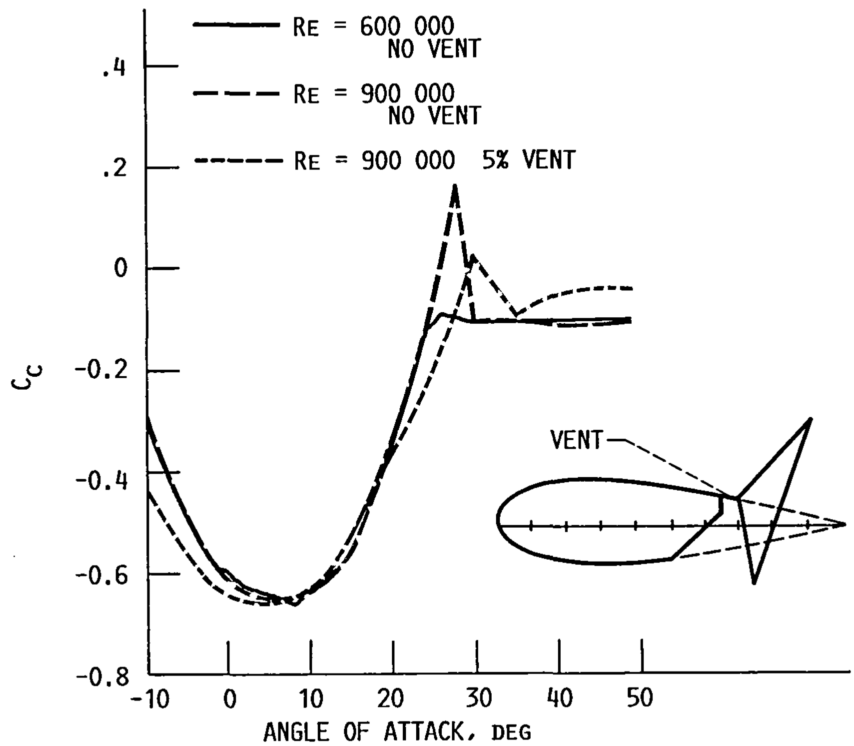
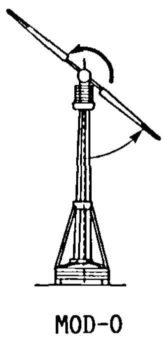


FIGURE 5. - EFFECT OF REYNOLDS NUMBER ON CHORDWISE FORCE COEFFICIENT, C_C (REF. 3).



STATION,	BLADE CHORD, M
.56	.56
1.02	.56
4.06	1.52
7.94	1.52
12.22	1.23
13.09	1.15
13.11	1.15
19.20	.67
19.50	.00

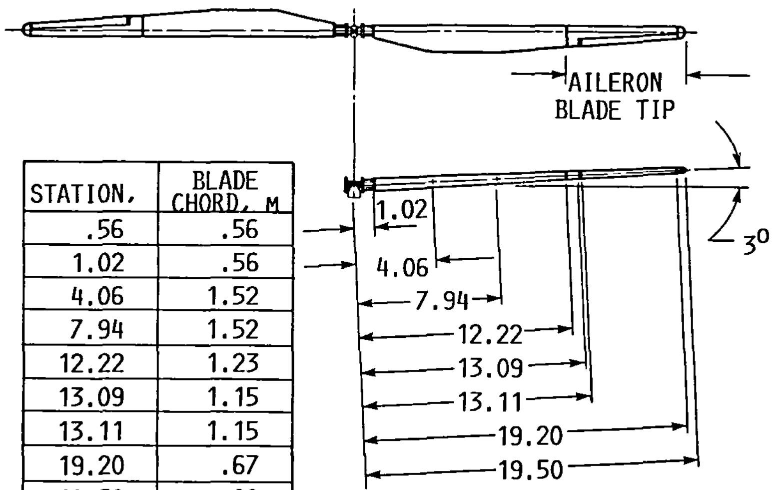
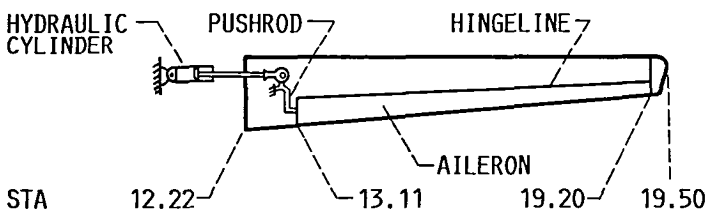


FIGURE 6.- MOD-0 AILERON-CONTROL ROTOR.



BLADE STA, M	BLADE STA, M	20% CHORD AILERON TIP		38% CHORD AILERON TIP	
		TWIST ANGLE, DEG	CONTROL CHORD, M	TWIST ANGLE, DEG	CONTROL CHORD, M
12.22	1.23	0	——	0	——
13.11	1.15	0	.25	3	.44
19.20	.67	0	.14	1	.25
19.50	——	——	——	——	——

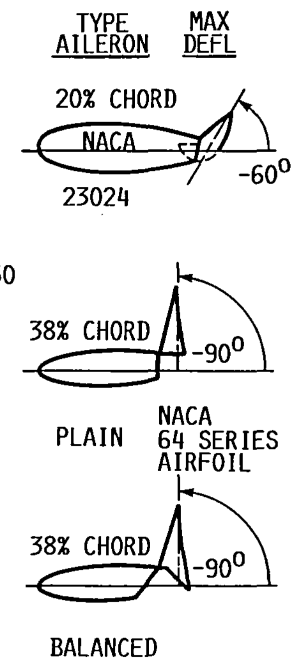


FIGURE 7.- COMPARISON OF 20 PERCENT AND 38 PERCENT CHORD AILERON-CONTROL TIP SECTION GEOMETRIES.

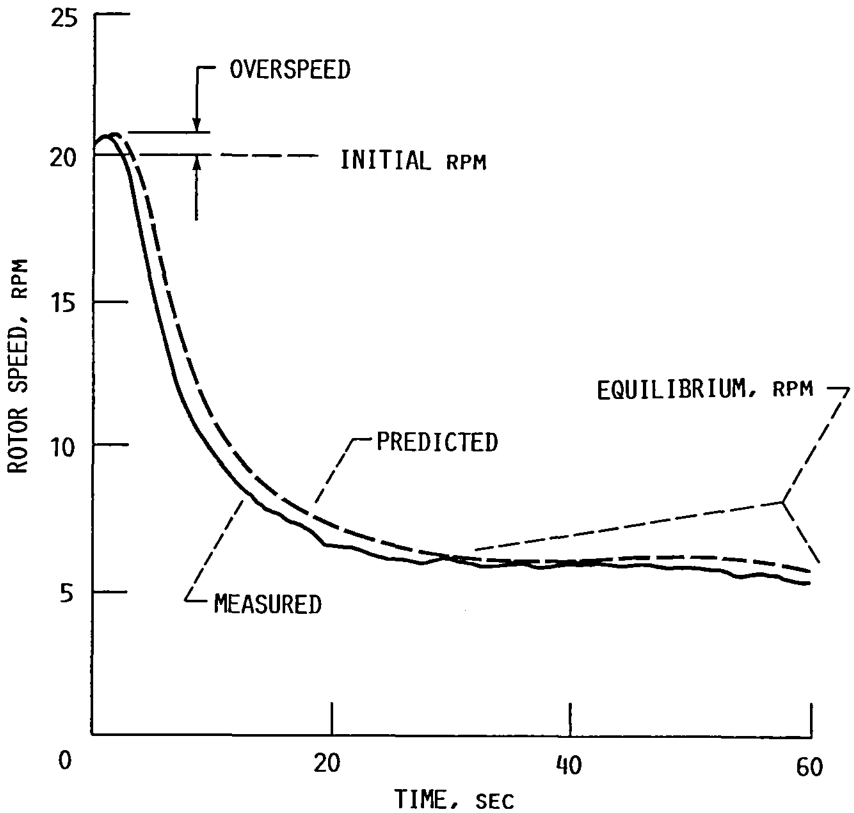


FIGURE 8.- TYPICAL LOSS-OF-LOAD SHUTDOWN FOR 38 PERCENT CHORD AILERON-CONTROL ROTOR.

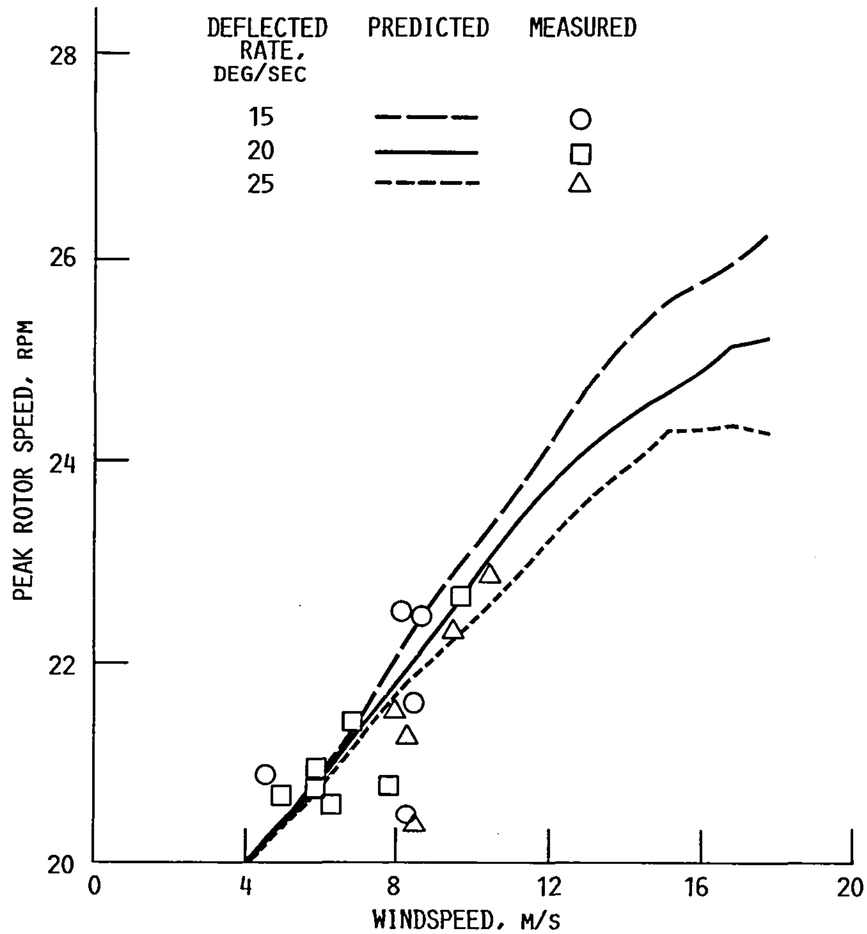


FIGURE 9.- PEAK ROTOR SPEED FOLLOWING LOSS-OF-LOAD FOR 38 PERCENT CHORD AILERON-CONTROL ROTOR (PLAIN CONFIGURATION, 2 AILERONS DEFLECTING).

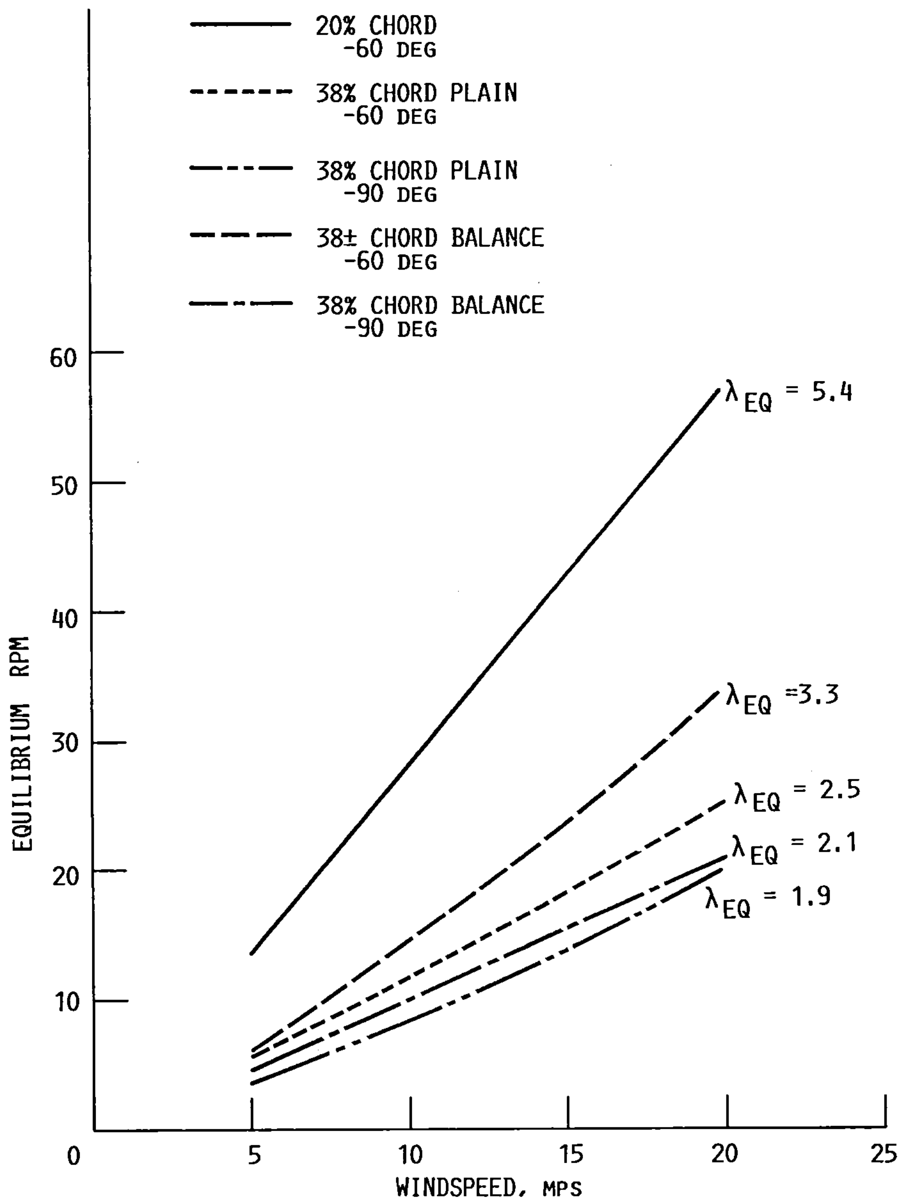


FIGURE 10. - NO-LOAD EQUILIBRIUM ROTOR SPEED FOR THE 20 PERCENT AND 38 PERCENT CHORD AILERON-CONTROL ROTORS.

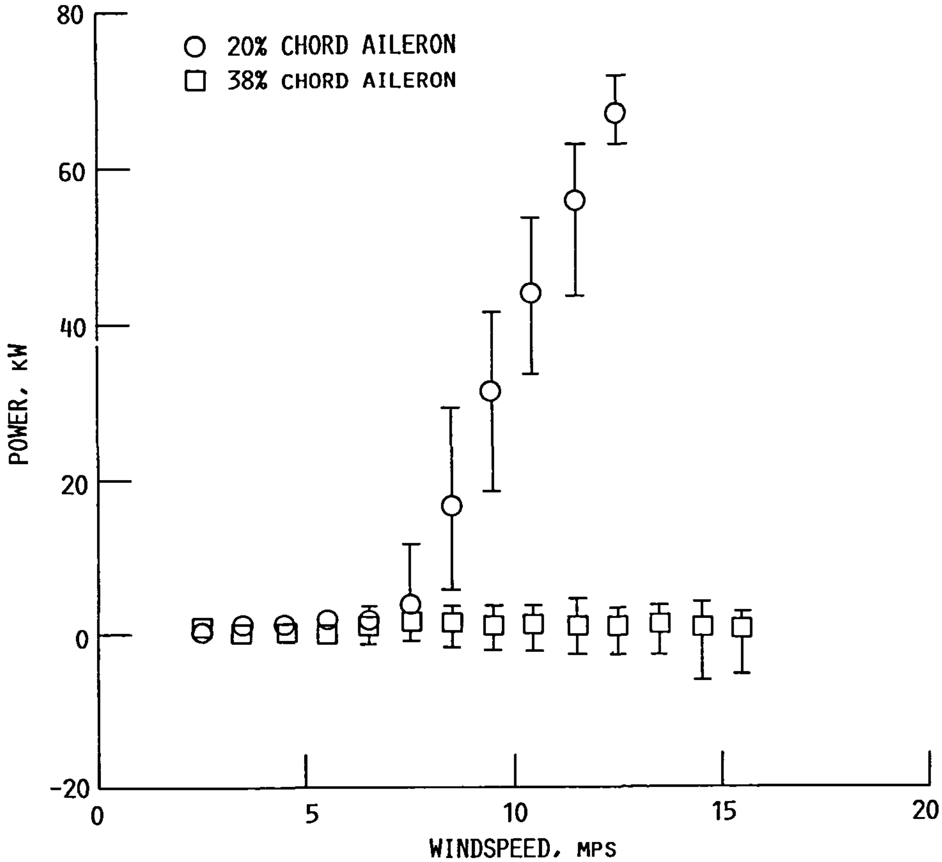


FIGURE 11.- POWER REGULATION FOR THE 20 PERCENT AND 38 PERCENT CHORD AILERON-CONTROL ROTORS (0 kW SETPOINT).

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16. Abstract
This paper will briefly trace the development of aileron-control for wind turbines. Then selected wind tunnel test results and full-scale rotor test results will be presented for various types of ailerons. Finally, the current status of aileron-control development will be discussed. Aileron-control was considered as a method of rotor control for use on wind turbines based on its potential to reduce rotor weight and cost. Following an initial feasibility study, a 20 percent chord aileron-control rotor was fabricated and tested on the NASA/DOE Mod-0 experimental wind turbine. Results from these tests indicated that the 20 percent chord ailerons regulated power and provided overspeed protection, but only over a very limited windspeed range. The next aileron-control rotor to be tested on the Mod-0 had 38 percent chord ailerons and test results showed these ailerons provided overspeed protection and power regulation over the Mod-0's entire operational windspeed range.

17. Key Words (Suggested by Author(s))
Wind turbine; Wind turbine rotor control; Aileron control

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